CLAY MINERALS IN THE PLAYA SEDIMENTS OF THE MOJAVE DESERT, CALIFORNIA

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ABSTRACT

Of all sedimentary environments, the desert lake stands out as the one environment in which clay minerals might undergo diagenetic change. By determining the clay minerals in the sediments from 45 playas in the Mojave Desert and comparing them with the clay minerals transported from the surrounding sources to the lake basin, new data concerning the effect of diagenesis on clay minerals in the continental saline environment were obtained.

Montmorillonite and illite, which was in all playas studied, made up at least 70 percent of the clay minerals present in all the playas except one. Chlorite and kaolinite were in the sediment of less than half the playas studied and generally made up less than 30 percent of the clay minerals present. In all cases the clay minerals of the playa sediments can be traced directly to the source areas surrounding the basins. Sepiolite-like clay minerals were not present in the samples studied.

The evaporite salts of the playas of southern California are rich in calcium and sodium; therefore, the conclusions of this paper may not apply to other continental saline environments rich in potassium and/or magnesium, or to the magnesium and potassium evaporites of marine origin.

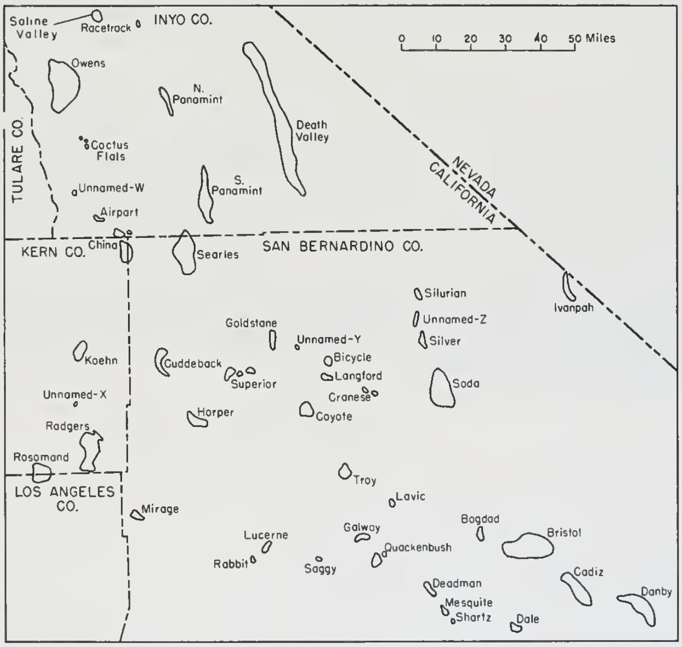

Figure 1. Index map showing the location of the playas sampled for this study.

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INTRODUCTION

In the last decade several papers have discussed clay minerals in sedimentary rocks and the effect of diagenesis on clay minerals in various sedimentary environments. This paper presents new data concerning the clay minerals in sediments and the effect of diagenesis upon clay minerals in the playas of southern California. Millot (1949) described clay-mineral associations in specific environments, and Grim, Dietz, and Bradley (1949), Grim (1951), Grim and Johns (1954), Keller (1956), and Grim (1958) suggested that some clay minerals are changed by diagenetic processes in the marine environment. Conversely, Weaver (1958), Milne and Eardley (1958), and Droste and Harrison (1958) reported that clay minerals in most sedimentary rocks are primarily the product of their source and have undergone little diagenetic change even in the marine environment.

This disagreement may be more apparent than real. Micas and chlorites are degraded by weathering and the many expansible clay minerals, called montmorillonite, in many soils are actually completely degraded sheet silicates. When these thoroughly degraded soil clays enter marine water the micas and chlorites selectively adsorb potassium and magnesium, respectively. The mica and chlorite structures may not reform immediately—perhaps not until long after burial. The formation of illite and chlorite from degraded sheet silicates might be considered diagenesis. The exchange reaction that occurs when the degraded sheet silicates enter marine water is not diagenetic, but the reconstitution of degraded soil clays to micas and chlorites after burial is diagenesis. If all investigators could agree on a definition of diagenesis, much of the difference in opinion would disappear.

It is generally agreed that little diagenetic change occurs in most nonmarine environments (Grim, 1951, and others); however, Millot (1949) has suggested the sepiolite-attapulgite clay minerals are formed in the super-saline lake environment. Millot, Radier, and Bonifas (1957) suggested that attapulgite is formed in the marine environment. From a detailed study of core material from Great Salt Lake, Grim, Kulbicki, and Carrozzi (personal communication, January 1959) reported that illite, kaolinite, and montmorillonite were present, but that none of the fibrous clay minerals were found. It is also noteworthy that regular sedimentary interstratification of different clay-mineral structures, such as corrensite, has been reported only in marine strata (Honeyborne, 1951; Lippmann, 1956; Bradley and Weaver, 1956; Bradley, Droste, and Grim, 1959).

In theory, high or low pH may make specific clay-mineral structures unstable. Many reports indicate that kaolinite is the more stable clay mineral in acid environments, but less stable in basic environments, and laboratory syntheses as well as natural deposits have been cited by many authors to substantiate the theory. If kaolinite is unstable in basic environments it should not be a stable phase in the saline facies of playa deposits.

With the generous support of the National Science Foundation the author has undertaken a study of the diagenetic effect of saline lake environment on clay minerals.

The Mojave Desert and the surrounding area in southern California contain more than 100 playas ranging in size from a few acres to more than 100 square miles. Forty-five of these lakes were sampled (fig. 1).

The lakes range in character from almost freshwater to very saline in which deposits of calcium and sodium salts as carbonates, sulfates, halides, borates, and others are found. A wide variety of source rocks surrounds the playa basins and the same source rocks shed sediments into playas with different chemical environments.

By comparing the clay minerals in the source materials with those in the playa sediments, important data concerning the diagenesis of clay minerals can be obtained.

Clay minerals in the surface samples from playas may not have had enough time to come to equilibrium with the evaporites; therefore detailed study of the clay minerals in evaporite bodies at depth may produce very useful information. Two hundred samples from bore holes deeper than 1000 feet, drilled by the United States Geological Survey, have been made available to the author for future study, and analyses of these samples will no doubt furnish much-needed data;* but for this report it was not possible to determine the effects of time, temperature, and pressure, important as they are in most diagenetic processes. Recent work by Powers (1959) shows that depth definitely produces changes in the clay minerals in marine sediments.

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* Data from the study of these core samples and surface samples from other playa sediments in California, Nevada, and Oregon confirm the observations made in this paper (Droste 1961a, 1961b).

ACKNOWLEDGMENTS

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Many lakes of the Mojave Desert are on private land, military reservations, and national reserves of various kinds, so that, without the permission and aid of the following persons, many of them would not have been approachable for study: Brigadier General R. M. Victory, Major R. H. McCormic, and Technical Sergeant R. O. McMahon, Marine Corps Base, Twentynine Palms, California; Lt. Commander L. G. Lewis and Mr. Val A. Cummins, U. S. Naval Ordnance Test Station, China Lake, California; Colonel T. C. McBride, Edwards Air Force Base, California; Major H. F. Tilley, Camp Irwin Military Reservation, California; Mr. F. W. Benneweis, Supt. Death Valley National Monument; G. S. Gordon, W. J. Diffley, W. H. Wamsley, and D. M. Cooper, U. S. Borax and Chemical Corporation; D. S. Dinsmoor, D. E. Garrett, and F. J. Dluzak, American Potash and Chemical Corporation; H. D. Hellmers and J. V. Wiseman, West End Chemical Company; W. C. Reeder, Ordnance Associates, Inc.; R. B. Diemer and L. L. Green, Metropolitan Water District of Southern California; H. H. Kerchkheff, Avawatz Salt and Gypsum Company; M. M. Stephens and P. T. Beeghly, National Chloride Company of America; F. W. Biedebeack, California Salt Company; L. E. Sowden, G. Cox, and B. Moffat, Dale Chemical Industries, Inc.; and Colonel and Mrs. S. S. Winslow, San Bernardino, California.

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Photo 1. Northern portion of Death Valley from Dante's View. ***Photo by Mary Hill.***

THE PLAYA SEDIMENTS

The provenance of the playa sediments is quite varied, and the detailed petrography of many of the rocks of the source areas is poorly known. Extensive Recent volcanic activity in the form of flows and ash has contributed to playa sediments, and Quaternary sedimentary deposits in the form of stream and lake terraces are found around many lake basins. Large thicknesses of Tertiary sedimentary and volcanic rocks are present throughout most of the Mojave Desert. A great volume of metamorphic rocks dated as pre-Cretaceous or Precambrian contributes clastic material to many playa basins. Igneous rocks, acid in composition and primarily of Mesozoic age, make up large parts of the mountains surrounding many desert basins, and Paleozoic marine metasedimentary rocks are abundant in some mountain ranges. All stratigraphic information in this report is taken from publications and maps of the California Division of Mines and other sources. For more detailed information the reader is referred to *Geology of Southern California* (Jahns 1954).

It is not practical to sample, for analysis, each variety of rock in a source area to learn the kind and amount of clay minerals it is furnishing to a playa deposit. The type and amount of clay material entering a playa can be determined by assuming that analyses of samples taken in the beds of major streams just before they enter the lake give the proper proportions of clay minerals contributed by all the source rocks. To see if alteration of clay minerals during transportation from source to playa would affect the proposed project, samples were taken along the courses of several streams, from their headwaters to where they entered the playa basin. It was found that the clay minerals about to enter the lake could not be differentiated from the clay minerals upstream.

Samples taken from the Mojave River illustrate this point (see table 2, under Soda Lake). The ratio of illite to montmorillonite in detritus from the San Bernardino Mountains is modified at Hellendale so as to increase slightly the montmorillonite content. At Manix the high montmorillonite content is related directly to the very high montmorillonite content of the Manix Lake beds of the area. One would expect changes such as these as detritus from new sources is added to a stream. Very careful examination of the X-ray patterns indicates that the degree of crystal perfection ("stacking", Roland, oral communication, November, 1959) is unchanged during transportation.

Most of the samples collected to represent the clay material of the source were taken from streams entering lakes containing extensive salt deposits, for it was assumed that the saline environment would bring about more diagenetic changes than the lake containing few dissolved solids. No difference was seen between the clay minerals in the playa, whether saline, brackish, or essentially fresh, and the clay minerals brought to it by streams.

This investigation does not purport to study and describe the details of playa sedimentation, but a few general statements about playa lakes can be made. It might be argued that very little, if any, material is being deposited on many of the playa surfaces at the present time, and that deflation may actually remove more material from the playa's surface than is deposited upon it. A small amount of precipitation falls upon the playas from time to time and occasionally flash floods carry material into the basins. Most of the playas have a shore facies of sand and gravel a mile or more wide. These permeable sediments soak up most of the precipitation that falls upon them; only the major arroyos that are fed by streams from the mountains are able to carry run-off with its load onto the playa surface. Some lakes are sinks of rather large river systems, as are Soda Lake for the Mojave River and Owens Lake for the Owens River.

The most common gravel-sized fragment on many playas of the Mojave Desert is vesicular basaltic lava. These fragments range in size from less than half an inch to 4 inches in diameter, and may have been slid onto the playa surface by the activity of wind or ice though their shape does not indicate it, some of these fragments may be volcanic bombs or blocks that were dropped on the lake surface during Recent volcanic eruptions in southern California. The abundance of these fragments, usually only partially buried by lake sediment, indicates that sedimentation in many playas is not rapid.

Samples of the playa surface sediments were taken from pick, shovel, and hand-auger holes. Pick and shovel holes about a foot deep yielded samples of the surface of the playas; these samples are assumed to represent material deposited in the lakes in the last few centuries. Auger samples were taken to a depth of about 10 feet.

Several kinds of surfaces are found on the playas in the Mojave Desert. One is the brown, dry, mud surface, with a dull silty clay appearance and a wide variety of mud cracks. It has no salt crust. Clay minerals are the last fragments to settle out onto the silty clay substrate, and as the lake dries they curl away from the silty clay beneath and are blown away by the wind. Another type of surface is the playa covered with a very rough, hard, thick salt crust such as at the Devils Golf Course in Death Valley. The salt of this surface is dominantly halite. An intermediate variety of surface is the dry lake with a thin ($\frac{1}{16}$-in.) salt crust over 6 to 8 inches of puffy, very porous, powder-dry material, often containing disseminated gypsum and halite crystals.

Some playas have more or less permanent saline lakes and marshes on their surfaces, and springs along the lake margin feed water into them continuously. Even on some of the dry mud lakes without any salt crust, moist sediments may be found at a depth of 1 to 2 feet, and in many lakes that have a salt crust, moist sediments are encountered just a few inches beneath the surface. Significantly, in marshes and lakes, and beneath deliquescent salt crusts, the lake sediment is usually a drab (olive or gray) color suggestive of a reducing environment, rather than the more common brown and red-brown colors of the oxidizing environment of the dry mud lakes.

The dry mud lake is easy to traverse and sample. Lakes with a thin salt crust are also easy to sample, but travel across them usually requires a vehicle with four-wheel drive. Lakes with thick, rough salt crusts can be crossed—with difficulty—but only on foot. A sample of the clastic material below the salt crust can be obtained only if the crust can be broken. In some cases a hole can be picked through it, but often hard-rock drilling and blasting must be used to break it. Lakes with wet sediments are hard to cross and present sampling problems. Some areas of the wet part of Soda Lake, for example, can be crossed with a four-wheel drive vehicle; but at Searles Lake, travel by vehicle on the wet part of the lake is restricted to causeways, and foot travel is accomplished by wading and "swimming" in playa mud. Samples of wet salty mud must be kept in glass bottles or plastic bags; also, the large salt content of the mud rapidly rusts augers, picks, shovels, and other field and personal equipment made of metal. Most salt layers more than 2 inches thick will stop the hand auger; such layers are common in the permanently wet muds.

CLAY MINERALS IN THE PLAYAS

Several groups of clay minerals are present in the playa sediments investigated in southern California. The identification of the minerals is based on X-ray analyses of powder and oriented samples; spectrograms were obtained for untreated, glycolated, and heated material. Fractionation was obtained by settling in water after removing soluble salts by solution in distilled water.

Oriented slides were made of the less-than-2-micron fraction by allowing 2.5 ml of clay slurry to evaporate on 27 by 46 mm glass slides. The glycolation was accomplished by placing the glass slide in contact with ethylene glycol vapor at room temperature. This is most conveniently done by filling the bottom of a desiccator with ethylene glycol and placing the slides in the glycol atmosphere for 24 hours.

In every sample some of the less-than-4-micron material contains clay minerals; but the majority of the material less than 4 microns and greater than 2 microns in size is made up of quartz, feldspar, mica, carbonates, sulfates, and other non-clay minerals. In the less-than-2-micron sizes, clay minerals usually make up at least 70 percent of the material; in the less-than-1-micron split, the clay minerals make up at least 85 percent of the sample.

Table 1 gives a quantitative estimate of parts in ten of the clay minerals of the less-than-2-micron size in selected samples from each playa. Analyses of the clay-mineral composition of source materials are not given for all samples as a number of samples have the same source area. Two nearby streams entering a playa basin may derive sediment from sources containing very different clay minerals, but the detritus from the two sources is often thoroughly mixed in the playa. An example illustrating this point can be taken from the Death Valley area. Samples from Coffin Canyon have a montmorillonite : illite : chlorite ratio of 5 : 4 : 1; those from Copper Canyon, just 2½ miles away, have a montmorillonite : illite : chlorite : kaolinite ratio of 2 : 5 : 2 : 1. A sample from the salt-pan just half a mile from the Copper Canyon fan has a montmorillonite : illite : chlorite : kaolinite ratio of 4 : 1 : 1 : 1; a sample at a lower level on the salt-pan about 2½ miles from the Copper Canyon fan and 3 miles from the Coffin Canyon fan has a montmorillonite : illite : chlorite ratio of 4 : 5 : 1. This demonstrates the ability of sheet-flood erosion and the normal stream dispersion of the Amargosa River to mix the

Table 1. Clay minerals of the less-than-2-micron size of playa sediments in the Mojave Desert.

NAME OF LAKE AND SAMPLE NO.	LOCATION				CLAY MINERALS PRESENT (Parts in 10)				
	Section								
	¼	No.	Township	Range	Montmorillonite	Illite	Chlorite	Kaolinite	Chlorite and/or kaolinite
Airport									
1	SE	26	23 S	39 E	5	5			
2	NE	28	23 S	39 E	5	5			
3	SW	21	23 S	39 E	6	4			
Bagdad									
1	NW	7	5 N	11 E	5	3	1	1	
2	NE	24	5 N	10 E	5	3	1	1	
3	SE	19	5 N	10 E	5	3	1		1
4	SE	7	5 N	11 E	6	3			1
5	NE	18	5 N	11 E	5	3	1		1
6	SW	18	5 N	11 E	5	3	1	1	
7	NW	19	5 N	11 E	6	3			1
8	NW	20	5 N	11 E	5	3	1	1	
Bristol									
1	SW	33	5 N	12 E	5	3	1	1	
2	SW	34	5 N	12 E	5	3	1	1	
3	NE	36	5 N	12 E	6	3			1
4	NW	36	5 N	12 E	6	3			1
5	SE	36	5 N	12 E	5	3	1		1
6	SE	26	5 N	12 E	5	3	1		1
7	NE	26	5 N	12 E	5	4			1
8	NW	26	5 N	12 E	5	3	1	1	
9	NE	27	5 N	12 E	5	3	1		1
10	SW	27	5 N	12 E	6	3			1
11	NW	27	5 N	12 E	5	3	1		1
12	SE	27	5 N	12 E	5	3	1	1	
13	NE	32	5 N	12 E	5	3	1	1	
14	NE	15	4 N	12 E	5	4	1		
15	NW	14	4 N	12 E	5	3	1	1	
16	NE	9	4 N	12 E	5	3	1	1	
17	NE	8	4 N	12 E	5	4			1
18	SW	5	5 N	12 E	6	3			1
19	SE	8	5 N	12 E	5	4	1		
20	SE	17	5 N	12 E	5	3	1	1	
21	SE	21	5 N	12 E	5	3	1	1	
22	NW	29	5 N	12 E	5	3	1		1
23	SE	29	5 N	12 E	5	3	1	1	
24	SW	33	5 N	13 E	5	3	1	1	
25	SW	4	4 N	13 E	5	3	1		1
26	SW	5	4 N	12 E	6	3			1
27	NW	8	4 N	12 E	5	4	1		
28	SW	31	5 N	12 E	6	3	1		
29	NW	6	4 N	12 E	6	3			1
30	SW	36	5 N	11 E	5	3	1		1
Bicycle									
1	SW	26	14 N	3 E	5	3	1		1
2	NE	35	14 N	3 E	5	3	1	1	
3	SW	34	14 N	3 E	5	3	1	1	
Cactus Flats									
1	SW	32	20 S	38 E	6	4			
2	SW	19	21 S	39 E	6	4			
Cadiz									
1	NE	4	2 N	15 E	5	3	1	1	
2	SW	3	2 N	15 E	5	3	1		1
3	SW	2	2 N	15 E	5	3	1		1
4	SE	9	2 N	15 E	5	3	1	1	
China									
1	NE	1	26 S	40 E	5	5			
2	SW	35	25 S	40 E	5	5			
3	NE	36	25 S	40 E	5	5			
4	SW	31	25 S	40 E	6	4			
5	SW	25	25 S	40 E	5	5			
6	SW	30	25 S	40 E	6	4			
7	NE	24	25 S	40 E	5	5			
Coyote									
1	NE	33	12 N	2 E	4	5	1		
2	SE	3	11 N	2 E	4	5	1		
3	NE	15	11 N	2 E	4	5			1
4	SE	2	11 N	2 E	4	5			1
5	SE	11	11 N	2 E	4	4	1		1
Cronese									
1	NE	18	12 N	7 E	6	4			
2	NW	19	12 N	7 E	6	4			
Cuddeback									
1	SW	22	30 S	42 E	4	5		1	
2	SW	4	31 S	42 E	4	5			1
Dale									
1	NE	27	1 N	12 E	5	4		1	
2	SW	27	1 N	12 E	5	4		1	
3	NW	26	1 N	12 E	5	4			1
4	SW	26	1 N	12 E	5	5			
5	NE	34	1 N	12 E	5	4			1
6	NW	35	1 N	12 E	4	5		1	
7	SW	35	1 N	12 E	4	5		1	
8	NE	26	1 N	12 E	5	4		1	
9	SE	26	1 N	12 E	5	4			1
Danby									
1	SE	3	1 N	18 E	4	4	1	1	
2	NW	11	1 N	18 E	5	4	1		
3	SE	10	1 N	18 E	4	5	1		
4	SE	11	1 N	18 E	4	5			1
5	NE	14	1 N	18 E	5	4	1		
6	SE	23	1 N	18 E	4	4	1	1	
7	SE	34	2 N	18 E	5	4	1		
8	NW	33	2 N	18 E	4	4	1	1	
9	NW	29	2 N	18 E	4	4	1		1
10	SE	20	2 N	18 E	4	4	1	1	
11	NE	23	2 N	17 E	4	5			1
12	SW	22	2 N	17 E	4	4	1		1
13	SW	15	2 N	17 E	4	4	1		1
Deadman									
1	SW	27	3 N	8 E					
2	NW	34	3 N	8 E					
3	NE	34	3 N	8 E					
4	SE	34	3 N	8 E					
5	SW	35	3 N	8 E					
6	NW	2	2 N	8 E					
Death Valley									
1	NW	32	28 N	1 E	3	6	1		
2	SE	32	28 N	1 E	3	6	1		
3	SE	9	27 N	1 E	3	6	1		
4	NE	14	17 S	47 E	4	5			1
5	SW	11	17 S	47 E	3	5	1		1
6	NW	9	17 S	47 E	4	5			1
7	NE	9	17 S	47 E	3	4			1
8	SE	6	27 N	1 E	4	5	1		
9	SE	1	17 S	47 E	4	5	1		
10	NE	6	27 N	1 E	4	5	1		
11	SW	31	28 N	1 E	4	5	1		
12	SW	1	17 S	46 E	4	5	1		
13	SE	1	17 S	46 E	5	4	1		
14	NE	33	16 S	46 E	4	5			1
15	SE	3	17 S	46 E	4	5			1
16	NE	3	26 N	1 E	6	3			1
17	NW	34	27 N	1 E	5	4	1		
18	SW	33	27 N	1 E	4	4	2		
19	SW	26	26 N	1 E	6	3	1		
20	SE	29	26 N	1 E	5	4	1		
21	NW	23	23 N	1 E	5	4	1		
22	NE	2	22 N	1 E	5	4	1		
23	NW	32	25 N	2 E	4	4	2		
24	NE	2	23 N	1 E	4	5			1
25	NW	22	24 N	1 E	3	6			1
26	NE	2	23 N	1 E	3	6			1
27	SW	4	23 N	2 E	4	4	1	1	
28	NE	29	25 N	2 E	5	4	1		
29	NW	33	25 N	2 E	4	4	2		
30	NE	2	22 N	1 E	3	6	1		
31	NW	1	22 N	1 E	4	5	1		
32	NE	23	23 N	1 E	4	5			1
33	NW	23	24 N	1 E	4	5	1		
34	NW	18	23 N	2 E	5	4	1		

Table 1. Clay minerals of the less-than-2-micron size of playa sediments in the Mojave Desert.—Continued

NAME OF LAKE AND SAMPLE NO.	LOCATION				CLAY MINERALS PRESENT (Parts in 10)				
	Section								
	¼	No.	Township	Range	Montmorillonite	Illite	Chlorite	Kaolinite	Chlorite and/or kaolinite
Death Valley—Cont'd.									
35	NW	24	23 N	1 E	4	5	1		
36	NW	22	22 N	2 E	4	5	1		
37	SW	29	23 N	2 E	5	4	1		
38	SE	7	22 N	2 E	4	5	1		
39	SW	9	24 N	2 E	4	4	2		
40	SW	1	23 N	1 E	4	5	2		
Emerson									
1	NW	9	4 N	6 E	6	3			1
2	NW	8	4 N	6 E	5	4	1		
3	NW	17	4 N	6 E	6	3	1		
4	SW	7	4 N	6 E	5	4	1		
5	SW	7	4 N	6 E	5	4			1
6	NW	6	4 N	6 E	5	4	1		
7	NW	7	4 N	6 E	5	4			1
8	NW	7	4 N	6 E	5	4	1		
9	NW	7	4 N	6 E	6	3	1		
Galway									
1	SE	4	5 N	5 E	7	2	1		
2	NW	8	5 N	5 E	6	3	1		
Goldstone									
1	SW	20	29 S	1 E	5	4			1
2	NE	29	29 S	1 E	5	4			1
3	SE	32	29 S	1 E	6	3			1
4	NW	30	29 S	1 E	5	4			1
Harper									
1	NW	17	11 N	4 W	5	4	1		
2	SW	8	11 N	4 W	4	5	1		
3	SW	27	11 N	4 W	4	5	1		
4	SW	23	11 N	4 W	5	4	1		
5	NW	23	11 N	4 W	4	5	1		
6	NW	25	11 N	4 W	5	4	1		
Ivanpah									
1	NE	18	17 N	14 E	5	4			1
2	NW	30	17 N	14 E	5	4		1	
3	SW	30	17 N	14 E	4	5		1	
4	NW	31	17 N	14 E	5	4			1
5	SW	32	17 N	14 E	5	4			1
Koehn									
1	SW	9	30 S	39 E	5	2	2	1	
2	SE	10	30 S	39 E	5	3	1	1	
3	NW	14	30 S	39 E	5	2	2	1	
4	SW	11	31 S	39 E	5	3	1	1	
Langford Wells									
1	NE	26	13 N	3 E	4	5	1		
2	NW	25	13 N	3 E	4	5	1		
Lavic									
1	NE	33	7 N	6 E	5	5			
2	NW	28	7 N	6 E	6	4			
3	SE	27	7 N	6 E	5	5			
4	SW	23	7 N	6 E	5	5			
5	SW	22	7 N	6 E	6	4			
Lucerne									
1	NE	14	5 N	1 W	2	6	2		
2	NE	23	5 N	1 W	2	6	1		1
3	NE	24	5 N	1 W	3	5	2		
4	SW	23	5 N	1 W	3	5	1		1
5	SW	26	5 N	1 W	3	6	1		
6	SW	27	5 N	1 W	2	6	1		1
Mesquite									
1	SW	29	2 N	9 E	3	5		2	
2	NW	32	2 N	9 E	3	5		1	1
3	SE	32	2 N	9 E	2	6		1	1

NAME OF LAKE AND SAMPLE NO.	LOCATION				CLAY MINERALS PRESENT (Parts in 10)				
	Section								
	¼	No.	Township	Range	Montmorillonite	Illite	Chlorite	Kaolinite	Chlorite and/or kaolinite
Mirage									
1	SW	34	7 N	7 W	1	3	6		
2	NW	2	6 N	7 W	2	3	5		
3	SE	1	6 N	7 W	1	3	6		
4	SE	7	6 N	7 W	2	2	6		
Owens									
1	NW	22	17 S	38 E	2	6	2		
2	SW	17	17 S	38 E	3	5	2		
3	NW	18	17 S	38 E	2	7	1		
4	NE	20	17 S	37 E	2	6	2		
5	NE	20	18 S	37 E	2	6	1		1
6	NE	21	16 S	37 E	3	5	1		1
7	SW	24	16 S	37 E	2	6	2		
8	SW	1	17 S	37 E	3	5	1		1
9	SW	16	16 S	37 E	2	6	2		
10	SW	23	16 S	37 E	2	7	1		
N. Panamint									
1	NW	1	19 S	42 E	3	4	2		1
2	SW	35	18 S	42 E	4	3	2		1
3	NW	23	18 S	42 E	6	3	1		
4	NW	10	18 S	42 E	6	3	1		
S. Panamint									
1	SW	4	23 S	44 E	5	3	1	1	
2	SW	34	23 S	44 E	5	3	2		
3	SW	22	23 S	44 E	4	4	1	1	
4	NW	14	23 S	44 E	5	3	1	1	
5	SE	23	23 S	44 E	5	3	2		
6	NW	23	23 S	44 E	4	5	1		
7	NW	24	23 S	44 E	5	3	1	1	
8	NE	24	23 S	44 E	5	3	2		
9	SE	8	22 S	44 E	5	3	1		1
10	NE	9	22 S	44 E	5	3	1		1
11	NE	16	21 S	44 E	4	4	1		1
12	NE	9	21 S	44 E	4	4	1	1	
Quackenbush									
1	NW	35	5 N	6 E	6	3	1		
2	SE	35	5 N	6 E	6	3	1		
Rabbit									
1	SW	6	4 N	1 W	4	4	1		1
2	SE	7	4 N	1 W	4	4	1		1
Racetrack									
1	SW?	31?	14 S	41 E	3	5	2		
Rodgers (Muroc)									
1	NE	18	10 N	9 W	4	5	1		
2	SE	17	10 N	9 W	4	5	1		
3	SE	15	10 N	9 W	5	4	1		
4	NW	28	10 N	9 W	4	5	1		
5	NE	27	10 N	9 W	5	4	1		
6	NW	35	10 N	9 W	5	5			
7	SW	17	9 N	9 W	4	5	1		
8	SE	16	9 N	9 W	4	5			1
9	NE	32	9 N	9 W	5	4	1		
10	NE	26	9 N	10 W	4	5	1		
Rosamond									
1	SW	30	9 N	11 W	2	5	3		
2	NE	6	8 N	11 W	3	5	2		
3	NE	4	8 N	11 W	3	5	2		
4	SW	28	9 N	11 W	2	5	3		
5	NE	20	9 N	11 W	2	5	2		
Saline Valley									
1	NE	27	14 S	38 E	3	6	1		

Table 1. Clay minerals of the less-than-2-micron size of playa sediments in the Mojave Desert.—Continued

NAME OF LAKE AND SAMPLE NO.	LOCATION				CLAY MINERALS PRESENT (Parts in 10)				
	Section				Montmorillonite	Illite	Chlorite	Kaolinite	Chlorite and/or kaolinite
	¼	No.	Township	Range					
Searles									
1	NE	31	25 S	43 E	8	2			
2	SW	4	26 S	43 E	7	2			1
3	NE	17	26 S	43 E	3	6			1
4	NE	16	26 S	43 E	4	5			1
5	NW	13	26 S	43 E	4	5			1
6	NW	33	25 S	43 E	6	3			1
7	SE	1	26 S	43 E	4	5	1		
8	NW	11	26 S	43 E	3	5	1	1	
9	NE	11	26 S	43 E	3	5	1	1	
10	NW	13	25 S	43 E	2	6	1	1	
11	NW	14	25 S	43 E	2	6	1	1	
12	SW	2	25 S	43 E	4	5	1		
13	NE	9	25 S	43 E					
14	SE	16	25 S	43 E	5	4	1		
15	SE	21	25 S	43 E					
16	NE	29	25 S	43 E	5	4	1		
17	NE	5	26 S	43 E	6	3			1
18	SW	24	25 S	43 E	4	4	1	1	
19	NW	26	25 S	43 E	4	5			1
20	SW	31	25 S	44 E	4	5			1
21	NW	5	26 S	44 E	3	5	1		1
22	SW	8	26 S	44 E	4	4	1		1
23	NW	18	26 S	44 E	4	4	1	1	
24	NE	30	25 S	44 E	2	5	2	1	
25	SE	30	25 S	44 E	2	5	2	1	
Shortz									
1	NW	15	1 N	9 E	3	6	1		
Silurian									
1	NE	25	17 N	7 E	3	5	2		
2	NW	30	17 N	8 E	2	5	2		1
3	SE	30	17 N	8 E	4	4	2		
4	NW	31	17 N	8 E	2	5	2		1
5	SE	31	17 N	8 E	2	5	2		1
Silver									
1	NE	21	15 N	8 E	7	3			
2	NE	28	15 N	8 E	6	3			1
3	NW	34	15 N	8 E	7	3			
4	NE	11	14 N	8 E	6	3			1
5	NW	13	14 N	8 E	7	7			1
Soda									
1	NE	11	12 N	8 E	3	6			1
2	NE	11	12 N	8 E	3	6			1
3	NW	12	12 N	8 E	3	6			1
4	NW	12	12 N	8 E	2	7			1
5	SW	36	13 N	8 E	3	6			1
6	NW	35	13 N	8 E	2	8			
7	SW	36	14 N	8 E	2	7			1
Soggy									
1	NE	8	4 N	3 E	2	5	3		
2	NE	8	4 N	3 E	3	6	1		
3	NW	8	4 N	3 E	3	6	1		
4	SE	8	4 N	3 E	2	6	1		
5	SE	6	4 N	3 E	2	5	3		
Superior									
1	NW	14	31 S	46 E	3	6			1
2	NW	14	31 S	46 E	4	5			1
3	NE	11	31 S	46 E	3	6	1		
4	SE	10	31 S	46 E	3	6			1
5	SW	17	31 S	46 E	4	5			1
Troy									
1	SW	33	9 N	4 E	6	3	1		
2	SW	4	8 N	4 E	5	4	1		
3	SE	3	8 N	4 E	5	4	1		
4	SW	9	8 N	4 E	6	3	1		
W (Unnamed)									
1	NW	32	22 S	37 E	5	5			
X (Unnamed)									
1	SW	3	12 N	9 W	4	4	2		
Y (Unnamed)									
1	SE	1	30 S	1 E	5	5			
Z (Unnamed)									
1	NE	31	16 N	6 E	6	3	1		

sediments from the two sources. Similar examples can be found in the Searles Lake sediments. In every case the variety and abundance of the clay minerals brought to the playa basin were recognized in the samples taken of the playa sediments. Only a few samples were taken from the smaller playas, but from the larger playas, several dozen or more samples were collected. The author feels that it is not advisable to list, for example, the clay minerals of the more than 100 samples of Death Valley sediments, for a great deal of repetition would result. However, samples included in table 1 (292 samples from a total of 413 analyzed) were selected to illustrate the general sample coverage of each playa and the range of clay minerals present. The clay minerals in 90 source samples, selected from the 127 analyzed, are shown in table 2. The numbers are quantitative estimates of the parts in ten of the clay minerals of the less-than-2-micron size fraction in each sample. The change in the ratios of one part in ten certainly is not significant in the data presented. The wide range in composition, the inability to recognize a very small amount of one clay mineral in the presence of several others, the uncertainty of equal degree of orientation in sample preparation, and the accidents of sampling, make a variation of two parts in ten in a few of the ratios insignificant.

Montmorillonite. Montmorillonite was in all samples. The ratio of montmorillonite to illite was estimated on the increase of the 10 Å peak after heating to 400° C. It was assumed that the increase of intensity of the 10 Å peak represented the collapse of montmorillonite, and that a direct ratio of the 10 Å peak before and after heat treatment indicated the relative abundance of illite and montmorillonite. At least two factors make it necessary to emphasize that this method gives only an estimate of the relative abundance of these two minerals.

Any degraded layers of illite or chlorite may collapse to 10 Å after heating, and montmorillonite may rehy-

drate slightly after heat treatment and before the sample can be X-rayed again. To avoid rehydration as much as possible, the sample was re-run as soon as the slide was cool enough to handle. Some organic matter absorbed by the montmorillonite might prevent complete collapse of the structure to 10 Å and at 400° C all of this organic matter may not be "burned out". Apparently two varieties of montmorillonite are in these playa sediments. One variety produces a narrow and intense (001) peak at about 17.0 Å after glycolation; this peak collapses at 10 Å after heat treatment. The second variety of montmorillonite has a more broad and less intense (001) peak as a rounded hump between 14.5 Å and 12 Å, and the (001) of the glycolated sample appears as a broader, and less intense, rounded hump between 18.5 Å and 16.5 Å. The (001) peak of the second variety does not collapse after heat treatment to the same extent as the first; also, the second variety rehydrates at a faster rate than the first. The significance of the two types of montmorillonite is not known. In a few samples rich in the first type a (060) diffraction peak (1.51 Å) indicates that the mineral is trioctahedral. The source of the two varieties is not known, but one may have formed from volcanic ash and the other from hydrothermal activity or weathering, etc. In many samples the two varieties apparently are physical mixtures. An attempt to estimate their abundance failed, in most cases.

Chlorite. A non-expanding, 14 A mineral is in many samples in subordinate amounts. In the oriented, untreated slides, its presence is suggested by (002), (003), and (004) peaks, and, if the montmorillonite content is low, the (001) peak can be seen in the glycolated slide. The (001) peak at about 14 Å is also seen after heat treatment if the mineral is well crystallized. This mineral is called chlorite in this report and is a major constituent of the less-than-2-micron material only in the sediments from one lake. The rough estimate of relative abundance is made by comparing the intensity of the (002) peak of the 10 Å mineral and the intensity of the (003) peak of the 14 Å mineral in the untreated sample. This method gives rise to a wide variety of possible errors, but chlorite is not a dominant mineral in these playa sediments, and some consistent scheme had to be selected. This system was chosen primarily from information obtained in analyses of artificial mixtures of chlorite and illite. A vermiculitic mineral is in a few samples and may be present in many others in slight amounts. In any case, it is included as a chlorite in tables 1 and 2.

Photo 2. Artist's Palette, on Artists' Drive, Death Valley. *Photo by Mary Hill.*

Illite. A 10 Å mineral is present in every sample. In the majority of cases the diffraction pattern would be considered to be the clay-mineral mica, illite, as defined by Grim, Bray, and Bradley (1937). The crystallizations of this 10 Å mineral in the playa sediments are dominantly 1 M and 1 Md. In some samples very sharp diffraction peaks are found that indicate a 2 M crystallization, and fine-grained detrital fragments of muscovite may actually be present. Many samples show weak to moderate asymmetry on the low-angle side of the 10 Å peak, indicating that the illite is partially degraded and that there may be a small amount of mixed-layered material in these samples. Some of the illite in the playa sediments exhibits the same features as the 10 Å material in weathering profiles (Droste, 1956; Droste and Tharin, 1958); that is, contains low to moderate amounts of degraded layers.

Kaolinite. Kaolite and chlorite are not abundant in most samples. The chlorite is easily identified by the (003) diffraction position in the untreated sample and by the (001) position in the heated sample; but some problem may arise in identifying a small amount of kaolinite in the presence of chlorite—for the (002) and (004) of chlorite are very nearly in the same position as (001) and (002) of kaolinite. Mixtures of kaolinite and other clay minerals have been run on the X-ray equipment of the Indiana Geological Survey and the Department of Geology, Indiana University. On both instruments the 3.51 Å spacing for (004) of chlorite and the 3.75 Å spacing for (002) of kaolinite are resolved. With copper radiation, this split is at 25° 2θ; the (002) peak for kaolinite is just below and the (004) peak for chlorite is just above the 25° 2θ position. The intensity of the (002) for kaolinite and the (004) for chlorite was compared directly to estimate the relative abundance of these two minerals. In those samples where the 14 Å mineral and the 7 Å mineral could not be differentiated, their abundance was estimated (see table 2, Chlorite and/or Kaolinite).

Mixed Layered Structures. A small amount of mixed layer material is present in many samples and the mixing is dominantly montmorillonite-illite. Because of the small amount of material, its abundance was not estimated. Heating to 400° C collapsed all layers to 10 Å and increased the intensity of the peak. The mixed layers are therefore reported as "montmorillonite" (see table 2).

Montmorillonite and illite are in all the playas studied and, even though their relative abundance is variable, they make up at least 70 percent of the clay minerals in all the playas except one. Mirage Lake has a unique clay-mineral distribution, as chlorite is dominent and illite and montmorillonite are subordinate clay minerals.

In every case the clay minerals of the playa surface material can be traced to source rocks surrounding the basins. In no case did any clay mineral of the sediments coming into the playa disappear in the lake environment. More than 100 samples of the salt-pan of Death Valley, furnished the author by Dr. C. B. Hunt, United States Geological Survey, were examined to see if the various salt environments would concentrate specific clay minerals by preferential flocculation. No correlation was found between the salt-pan facies and the variation in clay minerals present. The chlorite in a few of the

Photo 3. Red Rock Canyon, on Highway 6 north of Mojave in Kern County. *Photo by Mary Hill.*

Table 2. Clay minerals of the less-than-2-micron size in samples representing the source areas surrounding the playas of the Mojave Desert.

LAKE AREA	SAMPLE LOCATION	CLAY MINERALS PRESENT (Parts in 10)				
		Montmorillonite	Illite	Chlorite	Kaolinite	Chlorite and/or kaolinite
Death Valley area						
Funeral Mountains	3 mi. NE of Beatty Junction	6	3			1
Park Village	2 mi. W of Nevares Springs	5	4	1		
Furnace Creek Wash	At Furnace Creek Inn	4	5	1		
Furnace Creek Wash	At Zabriskie Point	3	6	1		
Furnace Creek Wash	Near junction with Corkscrew Canyon	3	6	1		
Desolation Canyon	At approximately 350′ above sea level	7	2	1		
Artists Drive	First Canyon N of south entrance	7	2	1		
Black Mountains	Second Canyon S of entrance to Artists Drive	6	3	1		
Black Mountains	NE of BM-248 near Natural Bridge	6	3	1		
Black Mountains	First Canyon S of Badwater	3	6	1		
Black Mountains	Third Canyon S of Badwater	3	6	1		
Black Mountains	Coffin Canyon	5	4	1		
Black Mountains	Copper Canyon	2	5	2	1	
Smith Mountains	Canyon at Mormon Point	4	5	1		
Panamint Range	Galena Canyon	4	5	1		
Panamint Range	Big Spring Canyon	3	6	1		
Panamint Range	Johnson Canyon	4	5	1		
Panamint Range	Starvation Canyon	3	6	1		
Panamint Range	Hanaupah Canyon	3	5	2		
Panamint Range	Death Valley Canyon	3	5	2		
Panamint Range	Trail Canyon	3	6	1		
Panamint Range	Tucki Canyon	3	6	1		
Emigrant Wash	At Emigrant Wash Ranger Station	6	3	1		
Amargosa River	Wingate Pass Wash	4	5	1		
Amargosa River	Central Amargosa Range, W side	5	4	1		
Amargosa River	Main Canyon to Owl Lake in Owlshead Mts.	4	5	1		
Amargosa River	Near Tecopa	7	3			
Amargosa River	Canyon to Salt Basin, Avawatz Mts.	6	3	1		
Amargosa River	Canyon to Sheep Creek Spring, Avawatz Mts.	4	4	1	1	
China Lake area						
Coso Mountains	Canyon E of Volcano Peak	6	4			
Coso Mountains	Canyon S of Volcano Peak	6	3			1
Argus Mountains	Canyon at SW end of the range	6	3			1
Argus Mountains	Canyon W of Argus Peak	4	5	1		
Louisiana Butte	Canyon trending SW of the Butte	4	4	1		1
Bristol Lake area						
Bristol Mountains	8 mi. NW of Amboy in valley between the Bristol Mountains and the Lava Hills	5	3	1	1	
Granite Mountains	9 mi. NE of Amboy in valley between the Bristol and Marble Mountains	4	4	1	1	
Ship Mountains	Canyon at S end of mountains, at McCoy	5	3	1	1	
Bullion Mountains	Canyon at NE end, 8 mi. E of Pacific mine	6	3	1		
Sheep Hole Mountains	3 mi. NE of Sheephole Summit	4	4	1	1	
Sheep Hole Mountains	6 mi. NNE of Sheephole Summit	4	4	1	1	
Dale Lake area						
Sheep Hole Mountains	4 mi. N of Bush	4	5	1		
Sheep Hole Mountains	Canyon of W-flowing stream from central part of the mountains	5	4	1		
Bullion Mountains	Main canyon, S end below Copper World iron mine	4	4	1	1	
Bullion Mountains	Canyon in SW ¼ T. 4 N., R. 8 E.	4	4	1	1	
		3	4	1	2	
Pinto Mountains	Canyon of N-flowing stream below Supply mine	2	5	2	1	
Dale Lake area—Cont'd						
Pinto Mountains	At Twentynine Palms	2	6	1	1	
Pinto Mountains	At Joshua Tree	3	4	1	2	
Danby Lake area						
Iron Mountains	NW-flowing dry wash in central part of mts.	3	5	1	1	
Old Woman Mountains	Wash in Ward Valley, 11 mi. NE of Milligan	5	3	1	1	
Turtle Mountains	Wash 5 mi. NE of Saltmash	6	3	1		
Turtle Mountains	Wash 4 mi. NE of Sablon	4	5	1		
Koehn Lake area						
El Paso Mountains	Dry wash at Garlock Station	6	2	1	1	
El Paso Mountains	At foot of Last Chance Canyon, 1 mi. SW of Saltdale	3	4	1	2	
El Paso Mountains	Dry wash 1 mi. NW of Gypsite	4	4	1	1	1
El Paso Mountains	At Redrock in Redrock Canyon	6	3			
Rand Mountains	Canyon flowing W of Sidney Peak area	3	4	2	1	
Owens Lake area						1
Owens River	At Bishop	5	3	1		
Owens River	At Big Pine	3	5	2		
Owens River	At Aberdene	3	6	1		
Owens River	At Kearsarge	2	6	2		
Owens River	At Lone Pine	2	6	2		1
Inyo Mountains	Canyon at Keeler	2	6	1		
Inyo Mountains	Canyon leading to New York Butte	2	6	1		1
Coso Mountains	Canyon leading to Centennial Springs	5	4	1		
Panamint Valley area						
Panamint Range	Canyon to Pinto Peak, along California Hwy. 190	6	3	1		
Panamint Range	Wildrose Canyon, at Wildrose	3	4	1	1	
Panamint Range	Hall Canyon	2	5	1	1	
Panamint Range	Pleasant Canyon	3	4	2		
Panamint Range	Valley between Slate and Panamint Ranges on San Bernardino County line	5	4	1		
Argus Range	Shepherd Canyon	4	5		1	
Argus Range	Knight Canyon	4	4	1	1	
Argus Range	At Panamint Springs	5	3	1	1	
Searles Lake area						
Salt Wells Valley	S end Argus Range	6	3	1		
Salt Wells Valley	Salt Wells Canyon	5	4	1		1
Argus Range	Canyon at west end	7	2			
Argus Range	Canyon 4 mi. NW of Trona	7	2	1		
Argus Range	Canyon in SE¼ T. 24 S., R. 42 E.	4	5	1		
Slate Range	Canyon on San Bernardino County line	3	5	2		
Slate Range	Canyon from central part of the range	5	3	1		
Slate Range	Canyon from southern part of the range	4	5	1		
Soda Lake area						
Mojave River	Near Hesperia	2	7	1		1
Mojave River	At Victorville	3	5	1		1
Mojave River	At Hellendale	4	4	1		1
Mojave River	At Barstow	3	6			1
Mojave River	At Manix	5	3	1		1
Mojave River	At Afton Canyon	4	5			1
Mojave River	At Crucero	3	6			1
Soda Mountains	Canyon, 4 mi. W of Baker	3	6			
Soda Mountains	Canyon, central part of Soda Mountains	3	6			1
Soda Mountains	Just below pass on U.S. Hwy. 91	4	6			

samples from Searles Lake appears to be slightly degraded, as seen by the loss of (001) after heating to 400° C. Most of the chlorite in all the samples studied is not changed by heat treatment. The chlorite entering Searles Lake is well crystallized and the very slight degrading may be the result of diagenesis in the saline environment, but data to date are inconclusive.

A few Pleistocene and Tertiary lake deposits were included in this study. Furnace Creek borate beds, Avawatz Mountain halite and gypsum beds, Kramer borate beds and other Tertiary deposits, and Pleistocene sediments of the Tecopa and Manix basins, as well as prepresent lake deposits in the China, Searles, and Panamint Valleys, were examined. Montmorillonite is the most common clay mineral of the Tertiary formations and the Tecopa and Manix beds. The older terraces found in the present basins contain the same clay minerals as the recent playa sediments.

The chemistry of the saline and super-saline evaporite salts in the playas of southern California is complex, but in every case the dominant cations are sodium and calcium. From the present study it is known that illite, montmorillonite, chlorite, and kaolinite are found in the very high-sodium environment as well as in the very high-calcium environment; for instance, in Bristol Lake halite is being mined as rock salt and the mother liquor is an ore of calcium chloride.

In the super-saline salts of marine environments, magnesium and potassium are important cations, and minerals such as sylvite, carnallite, longbeinite, and bischofite are formed. In the playa salts the potassium- and magnesium-bearing minerals (hanksite, tychite, and northupite) are rare, and make up a very minor part of the salt deposits. Therefore, it is not safe to assume that the information obtained from a study of continental evaporites may be applied entirely to all marine evaporites. The dominance of magnesium and potassium instead of sodium and calcium may make a great deal of difference. Very little work has been done on the clay-mineral content and variation in marine evaporite facies, but it is in these facies that the regular interstratification of two different clay-mineral structures have been found. These rare, regular, mixed-layer clay minerals are usually high in magnesium and are very probably diagenetic products. It is, therefore, very obvious that no categorical statements can be made until a great deal more information is available.

CONCLUSIONS

The clay minerals of the surface sediments in playas of the Mojave Desert are montmorillonite, illite, chlorite, and kaolinite. Their origin is in the source rocks and their weathering products surrounding the desert basins; and there is little evidence that any of them are unstable in the sodic and calcic saline-lake environment. The slight indication that chlorite is degraded in the Searles Lake sediments is not regarded at this time to show that chlorite is unstable in the saline-lake environment. It is hoped that detailed study of the Searles, China, Owens, Panamint, Bristol, Cadiz, Danby, and Soda Lake cores will shed light on the stability of chlorite in the playa. Sepiolite-attapulgite minerals are not present in any of the present playa muds which were sampled.

Although the chemistry of the playa salt facies is complex, the dominance of sodium and calcium and low concentrations of magnesium and potassium make it impossible to extend the conclusions of this paper to marine evaporite facies or to a lacustrine environment with a high magnesium content. The kind and abundance of the cation in the super-saline liquors may be the most important factor in diagenesis of clay minerals in evaporite deposits. Further investigation of core samples taken from the playa sediments of southern California may modify the conclusions reached in the present study.

Photo 4. Furnace Creek Wash, Death Valley. *Photo by Mary Hill.*

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Photo 5. Argus Range, Panamint Valley, and Panamint Range. *Photo by Mary Hill.*

Photo 6. Playa of Owens Lake near Keeler, from Cerro Gordo road. *Photo by Mary Hill.*

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